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COMPUTATION OF A HEMISPHERICAL RADIATOR FOR CALIBRATING PYRGEOMETERS

T. D. Voytikova

ABSTRACT

Calculations are presented for the radiation coefficients of a black hemispherical radiator for various ratios of the radius of the hemisphere to the diameter of the radiating aperture, and various coefficients of blackness of the internal cavity surface. An investigation was made of the effect of the device on the radiation coefficient of the cavity; we also investigated errors which occur because of the inaccurate measurement of the surface temperature.

1. Calculation of the Radiation Coefficient for an Absolute Blackbody of Hemispherical Shape

At the present time the calibration of pyrgeometers is accomplished by using "snowy sky" or a blackbody of hemispherical shape. The former method is used to calibrate the Angström and Fal'kenberg pyrgeometers, while the blackbody is used, e.g., by Stern and Schwartzman (ref. 5) and by V. L. Gayevskiy (ref. 2). However, the radiation coefficient of these standards is not accurately known.

The present work is devoted to the investigation of the radiation coefficient of an absolutely black radiator of the type described in reference 2. Because it is difficult at the present time to measure the radiation coefficient experimentally, several theoretical calculations were carried out.

The question of calculating the coefficients of blackness of hollow bodies is treated most completely in references 3 and 4. The calculation of the blackness coefficient for several specific cases of a cylindrical radiator is carried out in reference 1. According to these two works, the calculation of the blackness coefficient of a hollow body may be carried out in two ways: first, by integrating the radiation over the entire surface of the radiating sphere in the direction of the aperture; secondly, by calculations also involving the integration of the reflection of the radiation falling on the aperture by the cavity. In the second case the emissive power of the cavity in the direction φ (with respect to normal) is given by $e(\varphi) = 1-R(\varphi)$, where $R(\varphi)$ is the reflection coefficient at angle φ.

Reference 3 has data on the radiation coefficients for hollow bodies of cylindrical or spherical shape, obtained in accordance with the first method. However, similar calculations for bodies of hemispherical shape are not presented.

The present work uses a scheme, analagous to the one presented in ref. 3, to compute the radiation coefficients of blackbodies of hemispherical shape for various ratios of the radius of the hemisphere to the diameter of the aperture R/d, and various radiation coefficients of black coatings of the radiating cavity ϵ_1. The solution is obtained for the general case when the temperature of the surface of the hemisphere T_1 and of the base T_2 and the corresponding radiation coefficients ϵ_1 and ϵ_2 are different. Reflection from the surface of a hemispherical blackbody was considered to be of the scattered type, while radiation was considered to be isotropic. The calculation was carried out by taking into account successively all of the fluxes originating in the cavity by the radiation of its walls and subsequent reflections. Since the temperature of the hemisphere and the base is different, it is more convenient to consider the radiation from each of these surfaces separately, taking into account the independence of the fluxes.

Let us consider first the fluxes from the radiation of the hemispherical surface into the aperture $a = \frac{\pi d^2}{4}$, and these same fluxes which come out of the aperture after reflections of various orders from the hemisphere and the base.

It is assumed that the first flux consists only of the direct radiation of the hemisphere into the aperture a of diameter d. Let us determine its magnitude. The radiation of the surface element of the hemisphere ds on a (fig. 1) will be

$$dI_1 = \frac{\varepsilon_1 \sigma T_1^4}{\pi} \frac{a \cos i \cos \theta \, ds}{R^2},$$

where i is the angle between the direction of radiation and the perpendicular to the radiating surface (in this case to the hemispherical surface). Since $ds = R^2 \sin \theta d\theta d\varphi$, we have

$$dI_1 = \frac{\varepsilon_1 \sigma T_1^4}{\pi} a \sin\theta \cos\theta \, d\theta \, d\varphi.$$

The radiation of the entire surface of the hemisphere into the aperture a may be obtained by integration

$$I_1 = \frac{\varepsilon_1 \sigma T_1^4}{\pi} a \int_0^{\frac{\pi}{2}} \int_0^{2\pi} \cos\theta \sin\theta \, d\theta \, d\varphi = \varepsilon_1 \sigma T_1^4 a. \tag{1}$$

The second flux into the aperture a is due to the radiation of the hemisphere onto itself and the reflection of this flux by it into the aperture. Because the total radiation of the hemisphere in all directions is equal to $2\pi R^2 \epsilon_1 \delta T_1{}^4$, while the radiation produced by it towards the base, as we can show, is equal to $\pi R^2 \epsilon_1 \delta T_1{}^4$, this flux will be

$$I_2 = \frac{\rho_1}{2} a \varepsilon_1 \sigma T_1^4. \tag{2}$$

The third flux which comes out of the aperture is due to the reflection of the radiation of the hemisphere from the base, and then a secondary reflection from the hemisphere into the aperture

$$I_3 = \frac{\rho_1}{2} \rho_2 \varepsilon_1 \sigma T_1^4 \pi \left(R^2 - \frac{d^2}{4}\right) \frac{a}{\pi R^2} = \frac{\rho_1}{2} \rho_2 \varepsilon_1 \sigma T_1^4 \left(1 - \frac{d^2}{4R^2}\right) a. \tag{3}$$

In a similar way we may follow the formation of an infinitely large number of fluxes, if we take into account the second, third, etc. orders, both from the base and from the hemisphere. If all these fluxes are successively added, we obtain a series which represents the sum of an infinitely decreasing geometric progression

$$\begin{aligned} I_S = \varepsilon_1 \sigma T_1^4 a \Big\{ 1 + \frac{\rho_1}{2}\left[1 + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right] + \frac{\rho_1^2}{4}\left[1 + 2\rho_2\left(1 - \frac{d^2}{4R^2}\right)\right. \\ \left. + \rho_2^2\left(1 - \frac{d^2}{4R^2}\right)^2\right] + \frac{\rho_1^3}{8}\left[1 + 3\rho_2\left(1 - \frac{d^2}{4R^2}\right) + 3\rho_2^2\left(1 - \frac{d^2}{4R^2}\right)^2 + \right. \\ \left. \rho_2^3\left(1 - \frac{d^2}{4R^2}\right)^3\right] + \dots \Big\} = \varepsilon_1 \sigma T_1^4 a \left\{1 + \sum_{n=1}^{n}\left[1 + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right]^n \frac{\rho_1^n}{2^n}\right\}. \end{aligned} \tag{4}$$ [1]

[1] $I_S = I_{sphere}$.

Now let us consider all of the radiation fluxes which exit from a, which are caused by the radiation of the base, and the subsequent multiple reflection of this radiation, both from the base and from the hemisphere.

The first flux is produced by the radiation of the base, which is reflected by the hemisphere into the aperture

$$F_1 = \frac{\rho_1}{2}\varepsilon_2\sigma T_2^4 a\left(1 - \frac{d^2}{4R^2}\right).$$

The second flux is due to the reflection of the radiation of the base into the aperture a, which has been reflected twice by the hemisphere,

$$F_2 = \frac{\rho_1^2}{4}\varepsilon_2\sigma T_2^4 a\left(1 - \frac{d^2}{4R^2}\right).$$

The third flux consists of radiation reflected twice by the hemisphere and once by the base, etc.

After taking the sum of all the infinite number of possible curves we obtain, as in the first case, an infinitely decreasing geometric progression

$$\begin{aligned} F_b &= \varepsilon_2\sigma T_2^4 a\left(1 - \frac{d^2}{4R^2}\right)\left\{\frac{\rho_1}{2} + \frac{\rho_1^2}{4}\left[1 + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right] + \frac{\rho_1^3}{8}\left[1 + \right.\right. \\ &\left.\left. + 2\rho_2\left(1 - \frac{d^2}{4R^2}\right) + \rho_2^2\left(1 - \frac{d^2}{4R^2}\right)^2\right] + \ldots\right\} = \\ &= \varepsilon_2\sigma T_2^4 a\left(1 - \frac{d^2}{4R^2}\right)\sum_{n=1}^{n}\left[1 + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right]^{n-1}\frac{\rho_1^n}{2^n}. \end{aligned} \qquad (5)^1$$

The total radiation of the hemisphere, if we take into account the radiation to the base and the hemisphere, will be equal to

$$I = I_s + F_b = \varepsilon_1\sigma T_1^4 a S_1 + \varepsilon_2\sigma T_2^4 a\left(1 - \frac{d^2}{4R^2}\right)S_2;$$

where

$$S_1 = \sum_{n=1}^{n}\left[1 + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right]^n\frac{\rho_1^n}{2^n};$$

$$S_2 = \sum_{n=1}^{n}\left[1 + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right]^{n-1}\frac{\rho_1^n}{2^n};$$

$$\lim_{n\to\infty} S_1 = \frac{1}{1 - \left[1 + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right]\frac{\rho_1}{2}}; \qquad \lim_{n\to\infty} S_2 = \frac{\frac{\rho_1}{2}}{1 - \left[1 + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right]\frac{\rho_1}{2}}.$$

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[1] $F_b = F_{base}$

The final equation for the radiation of a blackbody of hemispherical form with different temperatures on the surface of the hemisphere and the base, and with different reflection coefficients for these surfaces, will be

$$I = \frac{\varepsilon_1\sigma\, T_1^4 + \varepsilon_2\sigma\, T_2^4\left(1 - \frac{d^2}{4R^2}\right)\frac{1-\varepsilon_1}{2}}{1 - \left[1 + (1-\varepsilon_2)\left(1 - \frac{d^2}{4R^2}\right)\right]\frac{1-\varepsilon_1}{2}}\, a. \tag{6}$$

From equation (6) we obtain an expression for the radiation coefficient of the cavity with respect to the radiation of an absolute blackbody having temperature T_1

$$\varepsilon_c = \frac{\varepsilon_1\sigma\, T_1^4 + \varepsilon_2\sigma\, T_2^4\left(1 - \frac{d^2}{4R^2}\right)\Big]\frac{1-\varepsilon_1}{2}}{\sigma\, T_1^4\left\{1 - \left[1 + (1-\varepsilon_2)\left(1 - \frac{d^2}{4R^2}\right)\right]\frac{1-\varepsilon_2}{2}\right\}}. \qquad (7)^1$$

In the case when $\epsilon_1 = \epsilon_2$, and the temperature on the surface of the base is equal to the temperature of the radiating hemisphere ($T_1 = T_2$), equation (7) assumes a much simpler form

$$\varepsilon_c = \frac{\varepsilon\left[1 + \left(1 - \frac{d^2}{4R^2}\right)\frac{1-\varepsilon_1}{2}\right]}{1 - \left[1 + (1-\varepsilon)\left(1 - \frac{d^2}{4R^2}\right)\right]\frac{1-\varepsilon}{2}}. \tag{8}$$

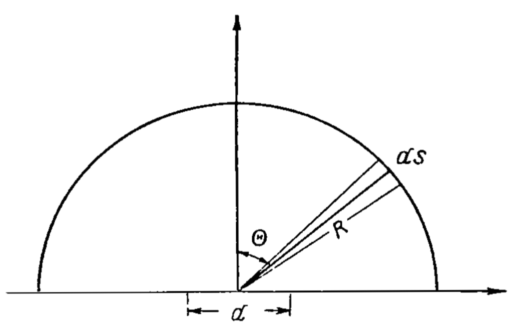

Figure 1.

[1] $\epsilon_c = \epsilon_{cavity}$

The radiation coefficients of hemispherical cavities computed by means of equations (7) and (8) for various ratios of the radius of radiating hemisphere to the diameter of its aperture and for various coefficients of radiation of black coatings of the hemisphere, are shown in Tables 1 and 2.

Table 1 is computed for a black hemisphere with the base covered with aluminum foil $\epsilon_2 = 0.054$, which in the first approximation is assumed to reflect by scattering.

Table 2 shows the radiation coefficients computed by means of equation (8) for the case $\epsilon_1 = \epsilon_2$ and $T_1 = T_2$.

TABLE 1. RADIATION COEFFICIENT OF A HEMISPHERICAL BLACKBODY FOR VARIOUS VALUES OF R/d AND ϵ_1

$\varepsilon_2 = 0{,}052$, $T_1 = 313^\circ$, $T_2 = 293^\circ$

ε_1	R/d											
	0,5	1,0	2,0	3,0	4,0	5,0	6,0	7,0	8,0	9,0	10,0	15,0
0,99	0,995	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,98	0,990	0,998	0,999	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,97	0,985	0,996	0,999	0,999	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,96	0,980	0,995	0,998	0,999	0,999	0,999	1,000	1,000	1,000	1,000	1,000	1,000
0,95	0,974	0,993	0,998	0,998	0,999	0,999	0,999	1,000	1,000	1,000	1,000	1,000
0,94	0,969	0,992	0,998	0,998	0,999	0,999	0,999	0,999	0,999	1,000	1,000	1,000
0,93	0,962	0,990	0,997	0,998	0,999	0,999	0,999	0,999	0,999	0,999	0,999	1,000
0,92	0,958	0,989	0,997	0,997	0,999	0,999	0,999	0,999	0,999	0,999	0,999	0,999
0,91	0,953	0,988	0,996	0,997	0,999	0,999	0,999	0,999	0,999	0,999	0,999	0,999
0,90	0,947	0,986	0,996	0,996	0,998	0,999	0,999	0,999	0,999	0,999	0,999	0,999
0,85	0,919	0,978	0,994	0,994	0,998	0,998	0,998	0,998	0,999	0,999	0,999	0,999
0,80	0,889	0,969	0,991	0,990	0,996	0,997	0,998	0,998	0,998	0,998	0,998	0,999
0,75	0,857	0,959	0,987	0,989	0,995	0,996	0,997	0,997	0,997	0,997	0,998	0,998
0,70	0,824	0,948	0,985	0,986	0,994	0,995	0,996	0,996	0,996	0,997	0,997	0,998

Commas indicate decimal points in this table.

TABLE 2. RADIATION COEFFICIENT OF A HEMISPHERICAL BLACKBODY WITH A BLACK BASE FOR VARIOUS VALUES OF R/d AND ϵ WHEN THE TEMPERATURE OF THE HEMISPHERE AND OF THE BASE IS THE SAME.

$$\varepsilon_1 = \varepsilon_2 = \varepsilon, \quad T_1 = T_2$$

ε	$\frac{R}{d}$											
	0,5	1	2	3	4	5	6	7	8	9	10	15
0,99	0,995	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,98	0,990	0,998	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,97	0,985	0,996	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,96	0,980	0,995	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,95	0,974	0,994	0,998	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,94	0,969	0,992	0,998	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,93	0,962	0,991	0,998	0,999	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,92	0,958	0,989	0,998	0,999	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,91	0,953	0,988	0,997	0,999	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,90	0,947	0,987	0,997	0,999	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,85	0,919	0,978	0,995	0,998	0,999	0,999	1,000	1,000	1,000	1,000	1,000	1,000
0,80	0,889	0,971	0,993	0,998	0,998	0,999	0,999	1,000	1,000	1,000	1,000	1,000
0,75	0,857	0,963	0,990	0,996	0,998	0,999	0,999	0,999	0,999	0,999	1,000	1,000
0,70	0,824	0,953	0,988	0,996	0,996	0,997	0,999	0,999	0,999	0,999	1,000	1,000

Commas indicate decimal points in this table.

2. Correction for the Radiation Coefficient due to the Radiation of the Device Undergoing Calibration

During the calibration of pyrgeometers the radiating aperture of the blackbody is closed by the sensing surface of the device, resulting in a closed cavity. The radiation falling on the device in this case may be different from the one computed by means of Tables 1 and 2, first, because of the radiation of the device itself and secondly, due to the reflection by the device of the radiation of an absolute blackbody. Let us evaluate the corrections due to both of these fluxes by considering their multiple reflection inside the cavity.

(a) Let us evaluate the correction due to the radiation of the device itself. Let the temperature of the device be T_3 and the area of the sensing surface be a. The area of the darkened part of the sensing surface is a_2, while the area of the nickelplated surface is $a_1 = a - a_2$. The schematic view from the top of the sensing surface is shown in figure 2.

ρ'' is the reflection coefficient for the black surface.

ρ' is the corresponding coefficient for the bright part of the device.

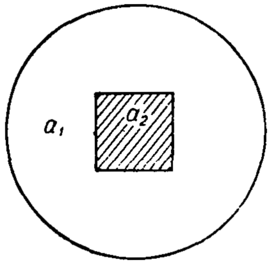

Figure 2.

The radiation of the sensing surface of the device towards the hemisphere will be equal to

$$I' = \varepsilon' a_1 \sigma T_3^4 + \varepsilon'' a_2 \sigma T_3^4 .$$

The radiation which has fallen on the sensing surface of the device after reflection from the hemisphere will be equal to

$$I'' = \frac{\varepsilon' a_1 + \varepsilon'' a_2}{2\pi R^2} \rho_1 \sigma T_3^4 a_2 .$$

Taking into account multiple reflections, Section 1, we find that this addition to the radiation coefficient of a black cavity due to the radiation of the device will be equal to

$$\Delta\varepsilon'_c = \frac{(\varepsilon' a_1 + \varepsilon'' a_2)\rho_1}{2 - \left[\left(1 + \rho' \frac{a_1}{\pi R^2}\right) + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right]\rho_1} \frac{\sigma T_3^4}{\sigma T_1^4} \frac{1}{\pi R^2} . \tag{9}$$

(b) Let us find the correction due to the reflection from the device. The radiation which is incident on the device from the hemisphere constitutes $\epsilon_c \delta T_1^4$ a. After reflection from the device, this radiation will produce a flux on the hemisphere which is equal to

$$F' = \varepsilon_c a_1 \rho' \sigma T_1^4 + \varepsilon_c a_2 \rho'' \sigma T_1^4 .$$

After reflection from the hemisphere, this flux will produce an "illumination" on the sensing surface, equal to

$$F'' = \frac{a_1\rho' + a_2\rho''}{2\pi R^2}\,\rho'\varepsilon_c\sigma T_1^4.$$

By taking into account F", and also all of the subsequent fluxes due to the multiple reflections, we find the correction for the coefficient ϵ_a due to the reflection from the sensor. This correction has the form

$$\Delta\varepsilon_c = \frac{[a - (\varepsilon' a_1 + \varepsilon'' a_2)]\,\rho_1}{2 - \left[\left(1 + \rho' \frac{a_1}{\pi R^2}\right) + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right]\rho_1}\,\frac{\varepsilon_c}{\pi R^2}. \quad (10)$$

Taking into account (9) and (10), we obtain a final form for the expression, giving the correction for the radiation coefficient of a hemispherical blackbody due to the effect of the calibrated device

$$\Delta\varepsilon_c = \frac{\rho_1\left[\varepsilon_c a - (\varepsilon' a_1 + \varepsilon'' a_2)\left(\varepsilon_c - \frac{\sigma T_3^4}{\sigma T_1^4}\right)\right]}{2 - \left[\left(1 - \rho' \frac{a_1}{\pi R^2}\right) + \rho_2\left(1 - \frac{d^2}{4R^2}\right)\right]\rho_1}\,\frac{1}{\pi R^2}. \quad (11)$$

By using this equation we compute the correction for the absolute blackbody, described in reference 2. In this case R/d=2, R=20 cm, a_1=9 cm^2, a_2=69.5 cm^2. Let $T_3 = T_2 = 293^\circ$. Let us assume that $\epsilon' = 0.15$, $\epsilon'' = 1$; ϵ is determined from Table 1. The correction for the radiation coefficient for various ϵ_1 computed by equation (11) is obtained from Table 3.

TABLE 3

ε_1	$\Delta\varepsilon_c$	ε_1	$\Delta\varepsilon_c$	ε_1	$\Delta\varepsilon_c$
0,99	0,000	0,94	0,0015	0,85	0,004
0,98	0,0005	0,93	0,002	0,80	0,006
0,97	0,001	0,92	0,002	0,75	0,008
0,96	0,001	0,91	0,0025	0,70	0,010
0,95	0,001	0,90	0,003		

Commas indicate decimal points in this table.

When we calibrate pyrgeometers we can, therefore, use a hemispherical blackbody when the geometric relation is $R/d = 2$ and the temperature difference is $T_1 - T_2 = 20^{\circ}$. Even if we have the worst possible blackness coefficients for dull coatings ($\epsilon_1 = 0.85$), the radiation coefficient of such a body (if we take into account the correction for the radiation of the sensing surface of the device) will be equal to

$$\epsilon_c = 0.994 + 0.004 = 0.998.$$

3. The Effect of Errors Incurred in Measuring the Temperature of the Radiator's Surface

The principal error incurred in measuring the radiation coefficient of an absolute blackbody is due to the error in measuring the temperature of the radiating surface. In the construction of the blackbody described in reference 2 it was assumed that the temperature of the radiating surface is equal to the temperature of the water washing this surface. With this type of construction the following errors are possible:

(1) errors due to the nonhomogeneous distribution of temperature over the radiating surface due to poor circulation of water and insulation;

(2) errors due to the fact that the temperature of the water does not correspond to the true temperature of the surface.

To reduce the first of these errors, continuous circulation of water was established with the aid of a thermostat. Measurement of the temperature by thermocouples at various points on the surface of the hemisphere and of the base (17 thermocouples) have shown that the maximum scattering between the individual points on the surface of the hemisphere is not more than $\pm 0.13^{\circ}$, which is within the limits of accuracy. The scattering at the base is substantially greater because of poor thermal insulation between it and the hemisphere. It reaches a value of $\pm 3^{\circ}$.

The temperature error may be evaluated by using equation (7)

$$\frac{\Delta\varepsilon_c}{\varepsilon_c} = \frac{4\left[\varepsilon_1 dT_1 + \varepsilon_2\left(\frac{T_2}{T_1}\right)^3\left(1-\frac{d^2}{4R^2}\right)\frac{1-\varepsilon_1}{2}\,dT_2\right]}{\varepsilon_1 T_1 + \varepsilon_2\left(\frac{T_2}{T_1}\right)^3 T_2\left(1-\frac{d^2}{4R^2}\right)\frac{1-\varepsilon_1}{2}} + \frac{4dT_1}{T_1}. \tag{12}$$

For the values of temperature distribution we assume that $dT_1 = 0^{\circ}$, $dT_2 = 3^{\circ}$. Then we have the following error for the computed body due to the nonhomogeneity of the temperature distribution on the surface

$$\frac{\Delta_1 \epsilon_C}{\epsilon_C} = 0.0001 \simeq 0.01 \text{ percent.}$$

The discrepancy between the temperature on the surface of the hemisphere and the temperature of the water heating it is clear from Table 4.

TABLE 4

t_{water}	$t_{surface}$	$t_{water}-t_{surface}$
20.40	20.00	0.40
20.50	20.40	0.10
20.65	20.50	0.15
21.20	21.00	0.20
45.30	45.45	-0.15
45.30	45.50	-0.20
33.90	34.30	-0.40

As we can see from Table 4, the maximum deviation of the true temperature of the surface from the temperature of the water does not exceed $\pm$ 0.4°. Substituting this value into equation (12), we obtain the possible error for the radiation coefficient due to the discrepancy between the true and measured temperature

$$\frac{\Delta_2 \epsilon_C}{\epsilon_C} \cong 0.01 \simeq 1\%.$$

Actually the error may be substantially less, because the accuracy for measuring the temperature of the water is $\pm$0.1°, while the accuracy of measuring the surface temperatures is of the order of $\pm$0.2°. We neglect the effect of the layer of air inside the cavity, because, according to our measurements, the difference in the temperatures between the surface of the blackbody and the air inside the cavity does not exceed 1° when the radiating aperture is open.

Thus, the radiation coefficient of the cavity of the type described in reference 2 will be equal to

$$\epsilon_c = 1.00 \pm 0.01.$$

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